

OBSERVATIONS OF HYDROGEN AND  
HELIUM ISOTOPES IN SOLAR COSMIC RAYS

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Hydrogen and helium isotopes in solar cosmic rays between 1.2 and 15.0 MeV/nuc have been observed with the Caltech Electron/Isotope Spectrometer on IMP-7. During 1973 three " $^3\text{He}$  rich events", containing more  $^3\text{He}$  than  $^2\text{H}$  or  $^3\text{H}$ , were observed on 14 February, 29 June, and 5 September. The latter event was particularly interesting in that  $(^3\text{He}/^4\text{He}) \sim 6$  and  $(^3\text{He}/^1\text{H}) \sim 1$ . Excluding these three events, flare-averaged ratios for  $^2\text{H}/^1\text{H}$  and  $^3\text{H}/^1\text{H}$  have been obtained for energies below 8.6 MeV/nuc. When compared with the ratios at higher energies, the observed energy dependence is consistent with the thin target model of Ramaty and Kozlovsky with a relativistic path-length of  $\sim 1 \text{ g/cm}^2$ . Flare-averaged  $^3\text{He}$  results reported here might suggest a somewhat longer pathlength.

**1. Introduction.** Nuclear reactions occurring in the solar atmosphere during flares promise to provide insight into particle acceleration mechanisms. The reaction products include gamma rays such as have been detected by Chupp *et al.* (1973), neutrons and positrons (yet to be directly detected) as well as secondary nuclei. Isotopic analysis of solar cosmic rays (SCR) at 1 AU provides a means of isolating such secondary nuclei since the rare isotopes of hydrogen and helium ( $^2\text{H}$ ,  $^3\text{H}$  and  $^3\text{He}$ ) do not constitute a significant fraction of the ambient solar atmosphere and so can be largely attributed to such reactions.

In this work flare-averaged observations of SCR isotopes are extended to lower energies than previously reported. In addition to flare-averaged measurements, three " $^3\text{He}$  rich flares" are discussed including one in which the relative abundance of  $^3\text{He}$  is the highest reported to date.

**2. Experiment.** The Caltech Electron/Isotope Spectrometer on the IMP-7 spacecraft is described elsewhere in these proceedings (Mewaldt *et al.*, 1975). In this paper, the mass, charge and incident energy of each analyzed particle is determined by a conventional dE/dx-E technique with a 50  $\mu\text{m}$  silicon detector (D2) measuring the energy loss and a 1 mm detector (D5) measuring the residual energy, with all other detectors in anticoincidence. Incident angles are limited to less than  $23^\circ$  with respect to the telescope axis for a geometrical factor of  $0.07 \text{ cm}^2\text{-sr}$ . Table 1 indicates the range of isotope energies which are detected as D2-D5 coincidence events.

Given the energy losses in D2 and D5, the mass and charge of each particle can be calculated and a mass histogram constructed. In order to determine isotope ratios in a given energy/nucleon interval, the  $^1\text{H}$  and  $^4\text{He}$  counts from the histograms must be adjusted for instrument response and to correspond to the same energy/nucleon interval as the rare isotopes. In all cases the dominant

error source is the statistical uncertainty in the rare isotope count. The mass resolution of the system is energy dependent, with the range of values shown in Table 1.

Table 1. Isotope Response for D2-D5 Coincidence Events

Isotope	Energy Range (MeV/nuc)	Mass Resolution $\sigma$ (amu)
$^1\text{H}$	2.4 - 12.7	0.05 - 0.14
$^2\text{H}$	1.6 - 8.6	0.10 - 0.21
$^3\text{H}$	1.2 - 6.8	0.15 - 0.28
$^3\text{He}$	2.9 - 15.0	0.12 - 0.22
$^4\text{He}$	2.4 - 12.8	0.16 - 0.27

3. Flare-Averaged Observations. Twenty-nine solar active periods between October 1972 and November 1973 were systematically identified using the rate of 2.4-13 MeV protons as a guide. With the exception of the  $^3\text{He}$  rich flares discussed below, no  $^2\text{H}$ ,  $^3\text{H}$  or  $^3\text{He}$  could be positively identified in any single period. The detection of flare-averaged  $^2\text{H}$  or  $^3\text{H}$  required that the background due to pulse-pileup and galactic cosmic rays be minimized. To accomplish this, a subset of the solar active data was selected so as to minimize the predicted background affecting the detection of  $^2\text{H}$  and  $^3\text{H}$ . This selection process systematically excluded the high rate peak periods of the larger flares when pulse-pileup is important and the less intense solar active periods and late stages of large events when galactic contamination is most serious. The criteria used for inclusion or exclusion were independent of whether any potential " $^2\text{H}$ " or " $^3\text{H}$ " was actually observed. This "optimized" flare sum included 11 solar active periods for a total of 29 days of observation.

The hydrogen mass histogram for this flare sum is shown in Figure 1. Since no  $^3\text{H}$  was observed, an upper limit for ( $^3\text{H}/^1\text{H}$ ) at the 84% confidence level can be set at  $3.4 \times 10^{-6}$  between 1.2 and 6.8 MeV/nuc.

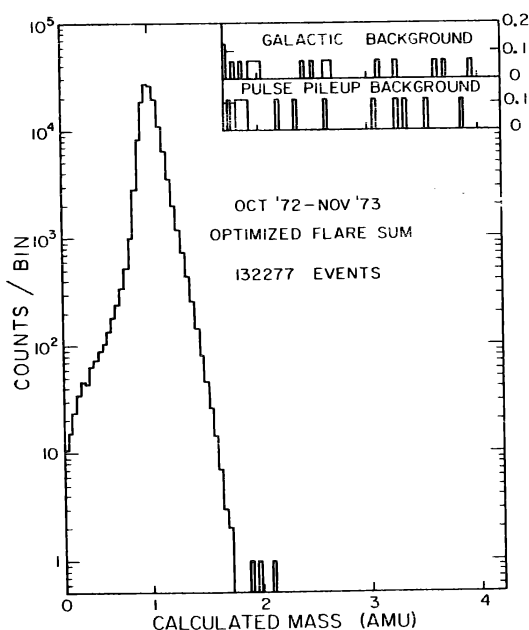


Fig. 1. Hydrogen mass histogram.

Figure 1 also shows the expected pulse-pileup and galactic background contributions scaled from observations during other time periods. Note that the background levels of  $\sim 0.1$  are offscale on the semi-logarithmic plot of the flare data and the flat spectral shape of each background component contrasts with the observed "peak" at 2 amu. Analysis of the expected background indicates that the best estimate of the number of deuterons observed is 2.0 so that ( $^2\text{H}/^1\text{H}$ ) is  $\left(7^{+10}_{-6}\right) \times 10^{-6}$  between 1.6 and 8.6 MeV/nuc.

To evaluate the flare averaged abundance of  $^3\text{He}$ , the full set of solar active periods identified above were combined, with only the  $^3\text{He}$  rich flares discussed below excluded from this sum. The measurement of small ( $^3\text{He}/^4\text{He}$ ) ratios is affected by channeling\* in the detector D2. The top panel in Figure 2 shows the flare-averaged helium mass histogram for energies 8 to 10 MeV, along with the predicted channeling background. The lower panel shows the corresponding histogram for higher energies, with an empirical background estimate. In both cases a small, but significant,  $^3\text{He}$  peak is observed. To improve statistical accuracy, the real  $^3\text{He}$  in both panels (3.1-15.0 MeV/nuc) is combined to yield ratios of ( $^3\text{He}/^4\text{He}$ ) and ( $^3\text{He}/^1\text{H}$ ) of  $0.009 \pm 0.004$  and  $(1.7 \pm 0.7) \times 10^{-4}$  respectively. On the basis of our solar quiet-time data, the galactic contribution to the observed  $^3\text{He}$  flux is estimated at less than 10%.

Figure 3 compares the present flare-averaged results with recent measurements by other workers. Ramaty and Kozlovsky, 1974 (R & K) have interpreted previous flare-averaged results in terms of a thin target model with relativistic path length,  $x_1 \sim 1 \text{ g/cm}^2$  (or equivalently  $x \sim 0.3 \text{ g/cm}^2$  at 30 MeV/nuc). The smooth curves in Figure 3 show the predicted ratios from R & K for assumed  $E^{-2}$  and  $E^{-3}$  differential primary spectra.

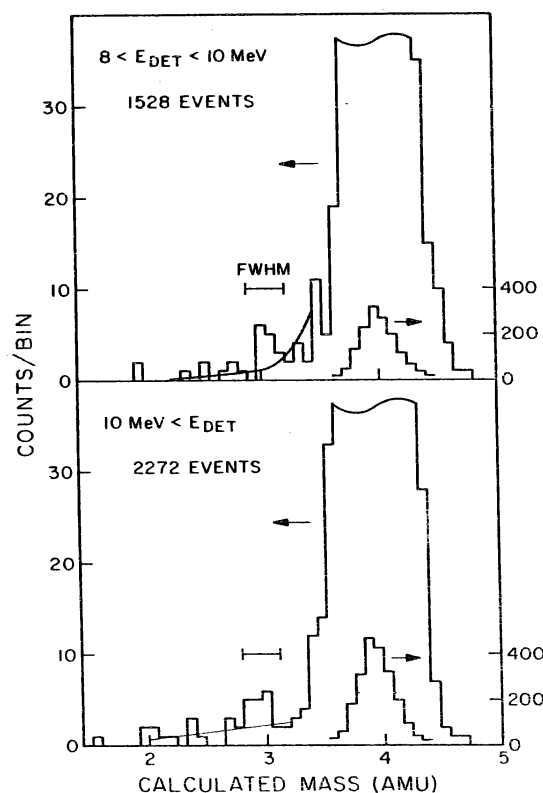


Fig. 2. Flare-summed helium mass histograms  $E_{\text{DET}}$  is the energy detected in D2 and D5.

\*Channeling causes a small fraction of SCR alpha particles, whose direction of incidence is parallel to a major crystal axis or plane in the D2 silicon crystal, to have an abnormally low rate of ionization energy loss and so contributes to a low mass tail to the alpha peak in the helium mass histogram. A channeling calibration experiment for 8.785 MeV alphas (Hurford, 1974) determined this tail to high statistical accuracy. The calibration is directly relevant to 8 to 10 MeV particles, but cannot be readily applied at higher energies.

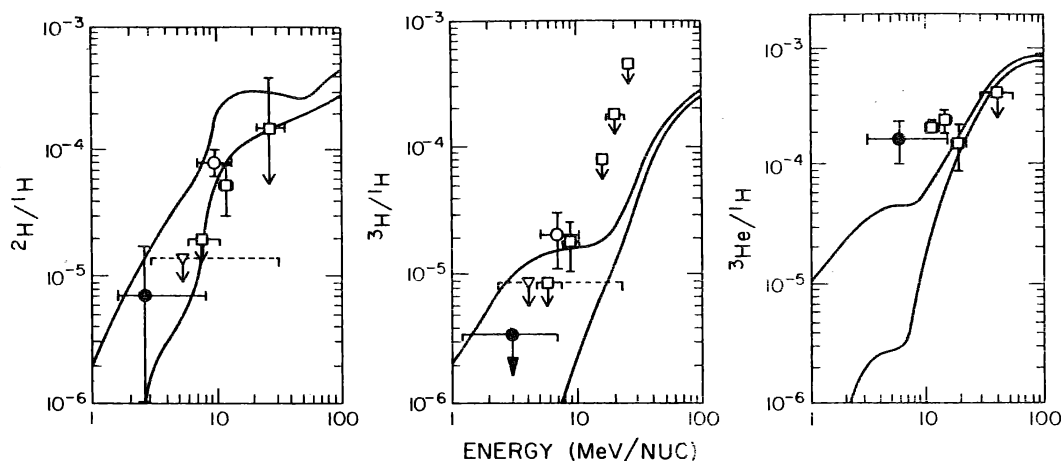


Fig. 3. Recent SCR isotope observations showing the flare-averaged data of Anglin, 1975 (open squares), Anglin *et al.*, 1973 (open circles), present work (solid circles) and observations of the 29 October, 1972 event by Rothwell *et al.*, 1973 (triangles). The upper and lower smooth curves are thin target model calculations derived from R&K and discussed in the text for differential primary spectra,  $E^{-2}$  and  $E^{-3}$  respectively.

Such models account for the trends in the  $^2\text{H}$  and  $^3\text{H}$  data but the low energy  $^3\text{He}$  observations suggest a somewhat longer pathlength. Alternative interpretations, such as contamination of the  $^3\text{He}$  flare-average by small  $^3\text{He}$  rich events, or the neglect of adiabatic deceleration (whose effect would be to shift the calculated curves to the left and smooth the spectral features), are possible. Of course, the possibilities of experimental error or the inappropriateness of the R & K thin target model also cannot be excluded.

4. Helium-3 Rich Flare Observations. A systematic search between 30 September 1972 and 9 January 1974 revealed three  $^3\text{He}$  rich flares, similar to those reported by Garrard *et al.* (1973), Serlemitsos and Balasubrahmanyam (1975) and Anglin (1975). The mass histograms for these are shown in Figure 4 and isotopic ratios given in Table 2. For each event the  $^3\text{He}$  fluence (3-15 MeV/nuc) was about

Table 2.  $^3\text{He}$  Rich Events Detected in 1973

Date	$^3\text{He}/^1\text{H}$ (2.9-15.0)*	$^3\text{He}/^4\text{He}$ (2.9-15.0)	$^4\text{He}/^1\text{H}$ (2.4-12.7)	Associated Flare
14 Feb	$0.05 \pm 0.02$	$0.21 \pm 0.07$	$0.27 \pm 0.03$	Radio event at 2054 UT. No optical flare patrol.
29 June	$0.09 \pm 0.04$	$\sim 2$	$0.06 \pm 0.02$	Importance -N optical flare at UT 0150, S13 W48.
5 Sept	$1.0^{+0.5}_{-0.4}$	$\sim 6$	$\sim 0.1$	Several subflares occurred in the hours preceeding the SCR event.

\*Energy intervals in MeV/nuc.

$300 \text{ cm}^{-2}\text{sr}^{-1}$ , which is about a factor of 3 above the threshold for detectability in this study. When combined with previous observations, the range of  $(^3\text{He}/^4\text{He})$  for such events is 0.2 to  $\sim 6$  while  $(^3\text{He}/^1\text{H})$  ranges from  $\sim 10^{-3}$  to  $\sim 1$ .

The 5 September 1973 event was remarkable in that much more  $^3\text{He}$  than  $^4\text{He}$  was observed and the fluxes of  $^3\text{He}$  and protons were about equal. This is the highest relative abundance of  $^3\text{He}$  reported to date. A solar origin for these  $^3\text{He}$  nuclei is supported by their steep energy spectrum, their arrival direction which was strongly anisotropic in the direction of the average magnetic field line from the sun, and their time profile. Figure 4 shows that a common characteristic of all three events is the absence of a detectable  $^2\text{H}$  or  $^3\text{H}$  flux, compared to the 33  $^3\text{He}$  observed with a higher threshold energy. In the energy interval of 2.9-6.8 Mev/nuc, common to all three isotopes, an 84% upper limit for  $(^2\text{H}/^3\text{He})$  and  $(^3\text{H}/^3\text{He})$  is 0.053, averaging over the three events. This result differs from the isotropic thick target yields of  $^2\text{H}$ ,  $^3\text{H}$  and  $^3\text{He}$  which are roughly in the ratio 2:1:3 (R & K).

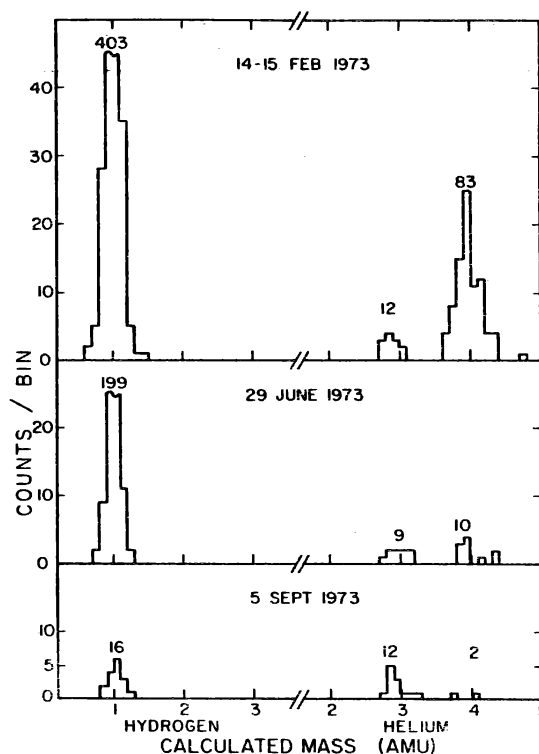


Fig. 4. Mass histograms for  $^3\text{He}$  rich flares observed in 1973. See Table 1 for the energy intervals for each isotope.

Although anisotropic thick target models such as proposed by R & K can account for some relative enhancement of  $^3\text{He}$ , such models have not proven adequate to explain all the  $^3\text{He}$  rich flare abundances reported to date (see, e.g., Serlemitsos and Balasubrahmanyam, 1975). In addition, recent observations have suggested that  $^3\text{He}$  rich flares may always be accompanied by enhanced fluxes of  $Z \geq 6$  accelerated particles (Hurford et al., 1975). This characteristic must also be accounted for by physical models of such flares.

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6. References.

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